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## FINAL REPORT

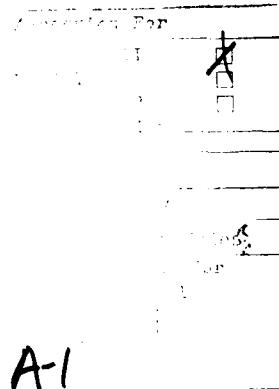
### FAST ACTING OPTICAL BEAM DEFLECTION SYSTEM

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DAJA 45-88-C-0019

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### SUMMARY

This report describes the results of a study of the nature of optical deflection in the wave length range of 300-1000 nm, using transmission gratings of two different surface relief profiles, i.e., blazed saw-toothed and phase sinusoidal types. The experimental results confirm the theoretical predictions and provide a quantitative comparison of the performances of the two profiles. An analysis of results leads to the recommendation of the sinusoidal profile in preference to the blazed (saw-toothed) gratings. A broad-band high attenuation across the optical to near infrared frequencies may be achieved by the use of 'crossed grating' structure with sinusoidal profile of judicious groove depth.

Of the four usable sinusoidal gratings provided by the Cambridge Consultants Ltd., the quality of the two photoresist grating materials was found to be superior to that of synthetic fused silica (hard etched).

## INTRODUCTION

The objective of the present work has been a study of optical diffraction phenomena in the pursuit of deflecting harmful coherent (laser) radiations in the wave-length range of 0.488 microns to 1.08 microns using transmission phase diffraction gratings. The familiar diffraction grating equation is (see figure 1).

$$d \sin \beta_m = m \lambda \quad \dots \dots \quad (1)$$

Where  $\beta_m$  is the angle of  $m$ th diffraction order,  $\lambda$  the wave-length of the incident optical radiation and  $d$  the grating period (i.e., lines per mm). It should be noted that the diffraction angle  $\beta$  is dependent only on the ratio of  $\lambda/d$  and not on the detailed structure of the grating. Equation 1 applies to any kind of diffraction grating including phase gratings in which a plane wave front is phase modulated by the surface relief to form secondary wavelets (see figure 2 and 3). For this work, our study has concentrated around two different blazed gratings profile, i.e., The blazed (saw-toothed) gratings, supplied directly by the USARDG and the sinusoidal gratings, provided by the Cambridge Consultants of the U.K.

### 1.1 Blazed Diffraction Grating (Saw-toothed Profile):

The general structure of a blazed transmission grating of saw-toothed profile is shown in figure 4. It consists of an optically transparent material of refractive index  $n_g$  attached to an optically transparent substrate of refractive index  $n_s$ . The depth of the profile is unimportant, the grating being defined by the groove angle  $\phi$ , and the period  $d$ . A blazed grating, in general, deviates more than 50% of the incident beam intensity into one of its two first order beams ( $m = -1$ ) for the condition  $\beta = \phi$ . Space  $\beta$  is dependent of the incident beam wave-length  $\lambda_b$ , this results in the grating being blazed for a particular wave-length  $\lambda$ , i.e., the light at or around the blaze wave-length  $\lambda$  is diffracted mostly into the first order beam ( $m +1$ ). From snell's law, at the grating facets, we have:-

$$n_g \sin \phi = \sin (\phi + \beta) \quad \dots \dots \quad (2)$$

(see figure 3). Combining equations 1 and 2 we get,

$$\phi = \tan^{-1} \left( \frac{\lambda_b}{n_g d - (d^2 - \lambda_b^2)^{1/2}} \right) \quad \dots \dots \quad (3)$$

Equation 3 allows a determination of the required blaze (groove) angle for the grating for a particular (blaze) wave-length  $\lambda_b$ .

## 1.2 Sinusoidally Blazed Phase Diffraction Grating

The diffraction efficiency of a sinusoidal phase grating is given by [1 - 3].

$$D_m = \left[ \left( \frac{1}{d} \right) \int_0^d \exp (2\pi i s(x) (n - 1) / \lambda - \left( \frac{m \pi d}{2} \right)^2) dx \right]^2 \quad \dots \dots \quad (4)$$

Where  $D$  is the efficiency of the  $m$ th order  $s(x)$  represents the relief of the grating, i.e.,  $y = s(x)$  in figure 3. The factor  $1/d$  provides a normalisation. Equation 4 is valid only for the case  $d \gg \lambda$ .

For a sinusoidal phase grating.

$$s(x) = \frac{a}{2} \sin \left( \frac{2\pi x}{d} \right) \quad \dots \dots \quad (5)$$

Where  $a$  is the peak to peak amplitude and  $d$  the grating period as before. Substituting equation 5 in equation 4, we get [1,3].

$$D_1 = J_1^2 \left[ \pi a (n - 1) / \lambda \right] \quad \dots \dots \quad (6)$$

Where  $J_1$  is the first order Bessel function of the first kind. Figure 5 shows the zeroth and first order diffraction efficiencies of a sinusoidal phase grating of amplitude  $a$  and refractive index  $n$ , as calculated from equation 6.

Figure 6 shows zero order transmission characteristics of phase gratings of different surface profiles [1].

## 2. Experimental Arrangements

The experimental arrangement is shown in figure 7 in which a monochromator was used as an optical radiation source of variable wave-lengths, the light beam being collimated by the lens system. A power meter sensor was used to detect and measure the intensities of the zeroth and first order beams as the wave-length was varied. Care was taken to reduce the background reflections to a minimum, as the light levels used was quite low, particularly in the region  $\lambda < 400$  nm.

### 3. Results & Discussions

#### 3.1. Replica Blazed Bratings (provided by USAR DSG)

The following gratings were investigated in this work.

Table 1. List of Available Blazed (Saw-toothed) Gratings

No	Grating Frequency $i/d$ (mm $^{-1}$ )	Blaze Angle $\phi$ (degrees)
1	300	4
2	300	17
3	600	8
4	600	13
5	600	17
6	600	28
7	632	45
8	830	30
9	1200	36
10	600	5 (Holographically Blazed)
11	1200	36 (Holographically Blazed)

The effect of varying of  $d$ -values at constant  $\phi$  is shown in figure 8, from which the variation in the blaze wave-length can be observed, along with a decrease in transmittance as the grating period  $d$ , was reduced. The effect of varying  $\phi$  at a constant grating period is shown in figure 9. The zeroth order transmittance appears to increase as  $\phi$  increases, which may be expected from a qualitative argument of the geometry of the grating. As  $\phi \rightarrow 0$ , the corresponding transmittance may be expected to approach 100% value as the grating surface becomes a plane.

Figure 10 shows the marked difference in the performance of blazed gratings of the same  $d$  and  $\phi$  - values, but manufactured using different methods. The blazed grating ( $d = 1200$  mm $^{-1}$  and  $\phi = 36^\circ$ ), produced holographically, appear to be considerably superior with respect to a lower transmittance in zeroth order beam in comparison with the conventional replica grating of the same  $d$  and  $\phi$  - values. A more detailed investigation into this phenomenon was not possible because of the limited availability of holographic gratings.

The best performance from a blazed grating was found with a 300 lines per mm and  $17^\circ$  blaze angle with a zeroth order transmittance of 3% at 545nm. Our interest is in the wave-length region of minimum zeroth order transmittance, thus defining the suitable band width of a grating (see figure 11). For blazed gratings, the optimum profile for a 300 lines per mm, and  $\phi = 17^\circ$  is given in Table 2.

Table 2. Optimum Profile of 300 lines per  $\text{mm}^{-1}$  and  $17^\circ$  blaze angle grating

Lower Cut-off Wave-length (nm)	Upper cut-off Wave-length (nm)	Band Width (nm)
420	680	260

3.2. Sinusoidal Phase Gratings

Four usable sinusoidal phase gratings were provided by CCL (Cambridge Consultants Limited). These gratings were produced by the NPL (National Physical Laboratories, U.K.) and Leybold AG (FDR) for CCL. The specifications are provided in the Appendix from which it may be observed that the grating materials for Grating Numbers C 3086/01 and C 3086/03 was photoresist whereas synthetic fused silica (spectrosil - B) was used as a grating material for the other two gratings (i.e. C 3086/05 and C 3086/10). An estimate of groove amplitudes was inferred from measurements of zero-order transmission by CCL and the respective values for the four gratings are given in Table 3.

Table 3. Groove Depths of Photo-Resist and Hard-Etched Sinusoidal Gratings

Grating Number	Grating Material	Grating Period (lines per mm)	Groove Depth - (nm)
C 3086/01	Photoresist Shipley Microposit 1400-17	600	755
C 3086/03	" "	" "	650
C 3086/05	Synthetic Fused Silica (spectrosil - B)	" "	550
C 3086/10	" "	" "	870

From theoretical considerations no effect on the wave-length response may be expected on varying  $d$  (i.e., lines per mm).

Figure 12 shows the effect of profile depth on zero-order transmittance width C 3086/01 and C 3886/03 photoresist gratings and figure 13 shows the corresponding behaviour with the etched gratings C 3086/05 and C3086/10. It is obvious from these results that the minimum of the zero-order transmission moves towards the infrared region of the spectrum as the profile depth is increased which is in agreement with the theory. However, a comparison between the two sets of results (figures 12 and 13) shows a marked difference in performance of the photoresist and hard etched gratings. The surface quality of the hard etched gratings are quite poor and further work is necessary in this respect. The band widths of sinusoidal gratings (for the two photoresist gratings) are given in Table 4, band widths being defined as the wave-length range for which zero-order transmittance is less than 10%, as in figure 11.

Table 4. Optimum Profile of Sinusoidal Phase Gratings C3086/01 and C 3086/03

Grating No.	Profile Depth (mm)	Lower Cut-Off Wave-length (nm)	Upper Cut-Off Wave-length (nm)	Bandwidth (nm)
C 3086/01	755	640	920	280
C 3086/03	650	595	840	245

It thus appears that the bandwidth of the optimised blazed (saw-toothed) and sinusoidal profiles are similar, each offering a minimum region of 260 - 280 nm. The sinusoidal profile is characterized by the low even orders in the intensity profile. In terms of the present application, it is required that the zero-order (and its close associates) transmission is reduced. Its performance in this respect, however, is superior to the blazed (saw-toothed) grating profile where the light around the blaze wave-length is deliberately propagated onto the first order. Blazed gratings also provide poor visibility. In view of this, it is difficult to see how the blazed (saw-toothed) gratings can be given a preference over the sinusoidal gratings for the present application, unless the danger from the large first order transmission is removed through the use of a large diffraction angle. It may also be noted that it is not possible to predict the behaviours of the blazed region, although the response of the sinusoidal phase grating is readily predicted. Thus the sinusoidal phase grating should aid the design of a wideband rejection of optical wave-lengths. Above arguments would suggest that the sinusoidal profile is superior to that of the blazed saw-toothed grating for the present application.

#### 4. Multiple Grating System

It has been shown [1] that the transmittance of a two gratings system is the product of the two individual grating transmittance. For two 'crossed' sinusoidal gratings of groove amplitudes  $a_1$  and  $a_2$  the transmittance is given by [1],

$$D(\lambda) = J_0^2(\pi a_1 / \lambda) J_0^2(\pi a_2 / \lambda) \dots \dots \dots \quad (7)$$

It has been found [3] that the use of more than two gratings does not provide any significant advantage because mixed diffraction orders can emerge close to the zero-order beam.

A two grating system was investigated experimentally using the two photo-resist sinusoidal gratings C 3086/01 and C 3086/03 and the arrangement, shown in figure 14 in which the grating A was located so that the plane of its corrugation was perpendicular to that of the grating B. This arrangement avoids the situation where a first order beam from the grating A is diffracted back into the zeroth order by the grating B.

The results are given in figure 15, which shows that the zero-order transmittance has been virtually eliminated in the wave-length region of 650 - 860 nm. It should be noted, however, that these results were obtained using the experimental apparatus at its limits and merely serve to indicate a possible area for future research.

The effect of a two grating system may be achieved by using a single two-dimensional sinusoidal phase grating as illustrated in figure 16,

(shown as a rectangular type for the ease of viewing). It may also be observed from figure 6, that triple step profile (figure 6, diagram 'f') represents a seemingly ideal solution for the present application which will allow a wide region of zero transmittance and thus provide protection from hazardous radiation, but still affording good transmittance outside the minimum regions to enable the pilot some vision.

Finally, a criticism must be levelled against the Cambridge Consultant Limited for providing us with so few sinusoidal gratings and so late in the day. The work also suffered from a lack of exacting data on groove depth. CCL should have provided more accurate information on groove depths.

In summary, it may be stated that the present work shows that with using photo-resist sinusoidal phase gratings with judicious choice and fabrication of groove depth and profile it is possible to achieve a zero-order transmission ( $\sim 5\%$ ) over a required bandwidth in the optical to near infrared wave-length.

#### References

1. M.T. Gale & K. Knop.  
'Surface Relief Images for Colour Reproductions'.  
Focal Press (London, New York), Chapter 2. pp 10-29 (1980)
2. L.P. Boivin.  
'Multiple Imaging Using Various Types of Simple Phase Gratings'.  
Applied Optics, 11 (8) pp 1782 - 1792 (1972)
3. M.T. Gale.  
'Sinusoidal Relief Gratings For Zero-order Reconstruction'.  
Optical Communications, 18, pp 292 - 297 (1976).

#### Appendix

Specifications of the four usable sinusoidal phase gratings, as provided by the Cambridge Consultants Limited (CCL).

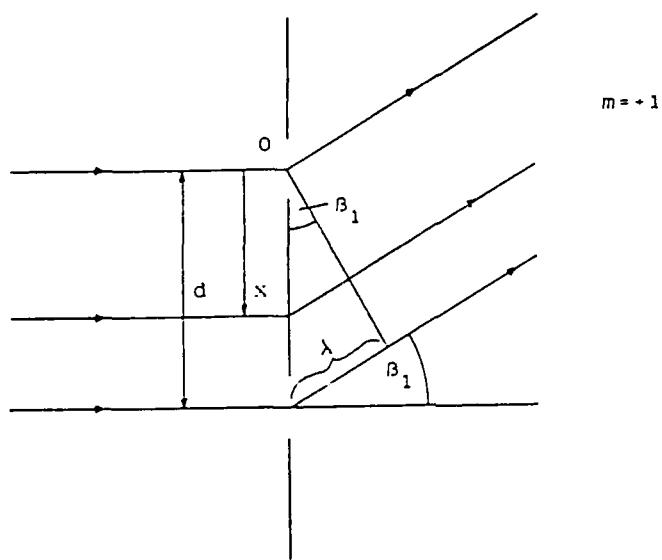


Figure 1. Constructive interference in First Order diffraction.

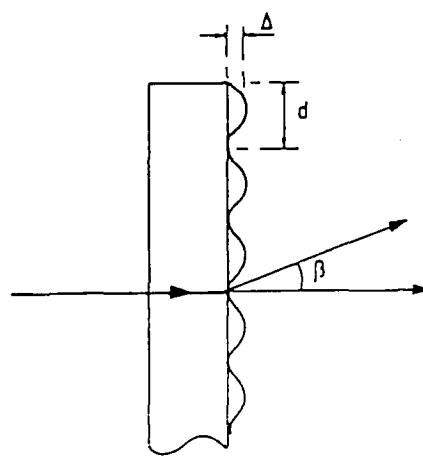


Figure 2 : General transmission phase grating.

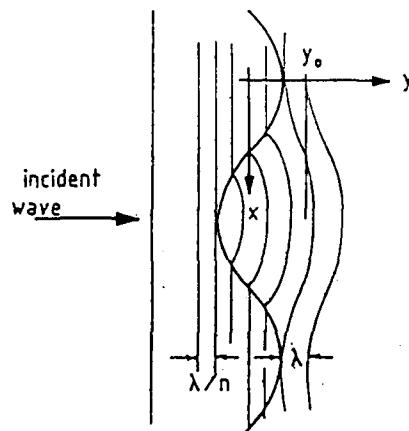


Figure 3 : Distortion of plane wave due to grating profile.

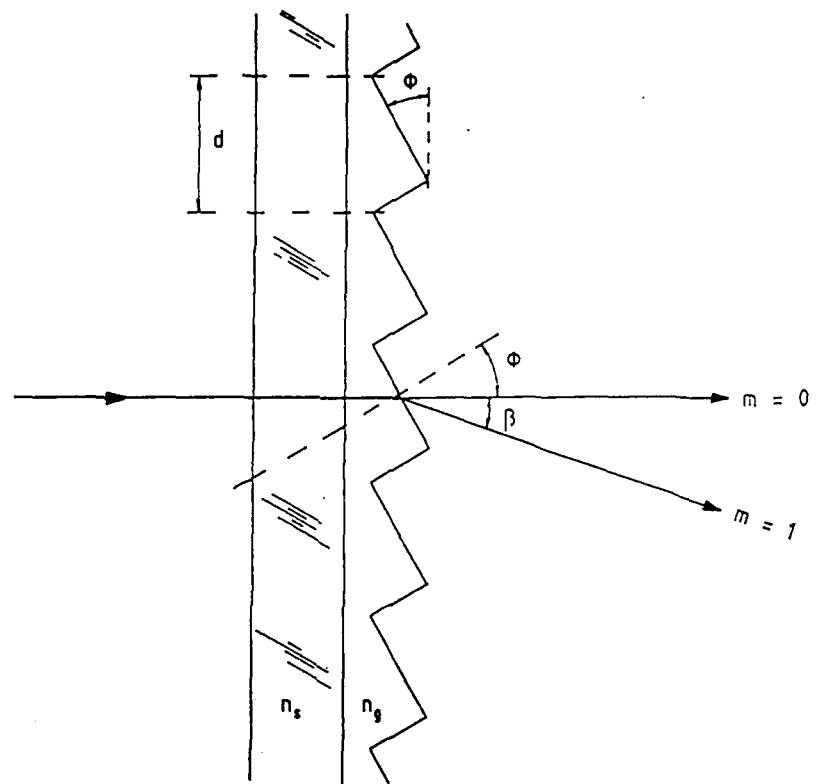


Figure 4 : Blazed transmission diffraction grating.

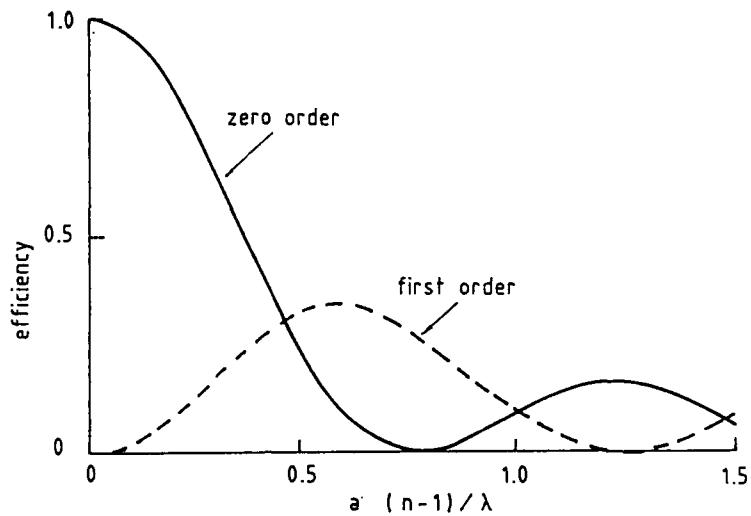


Figure 5 : Zero and first order diffraction efficiencies of a sine-wave phase grating ( amplitude  $a$ , medium refractive index  $n$  ) as calculated from Equation 8.

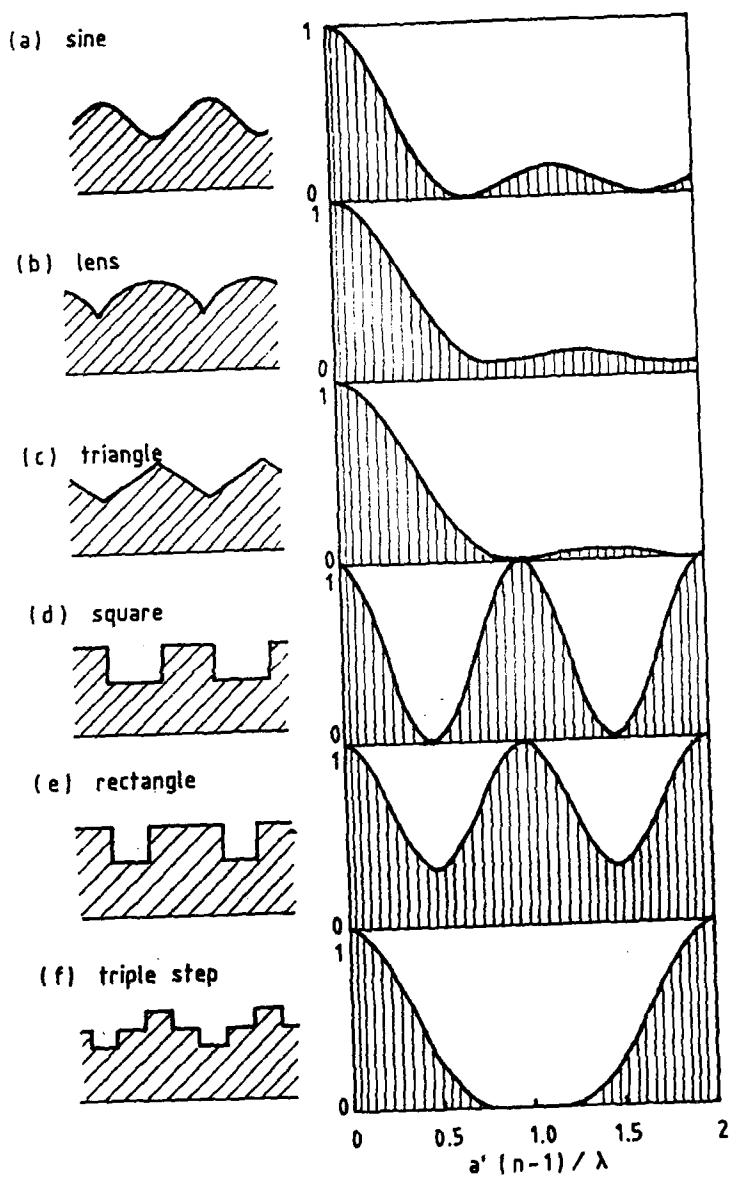


Figure 6. Zero-order transmission characteristics of various phase gratings (from reference 1).

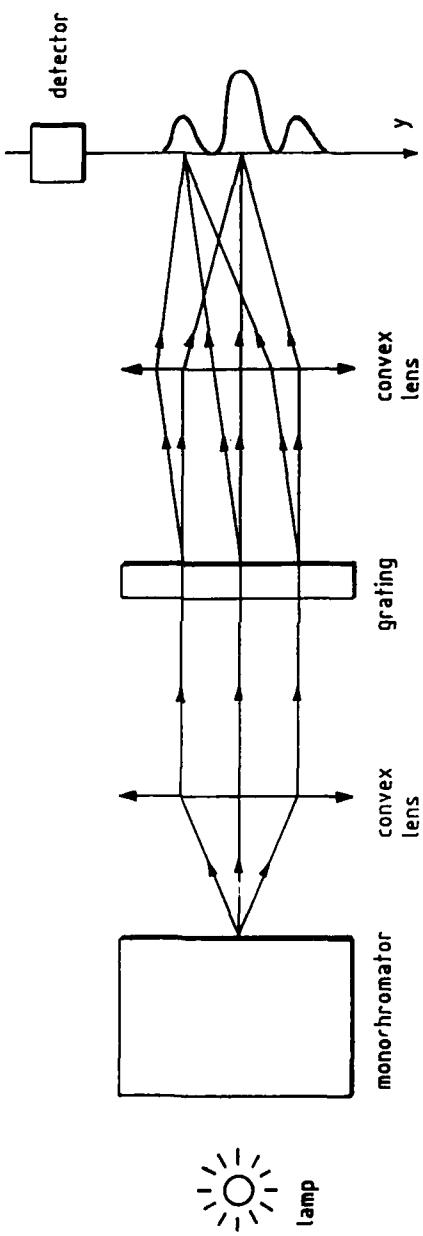


Figure 7 . Wavelength response experimental arrangement.

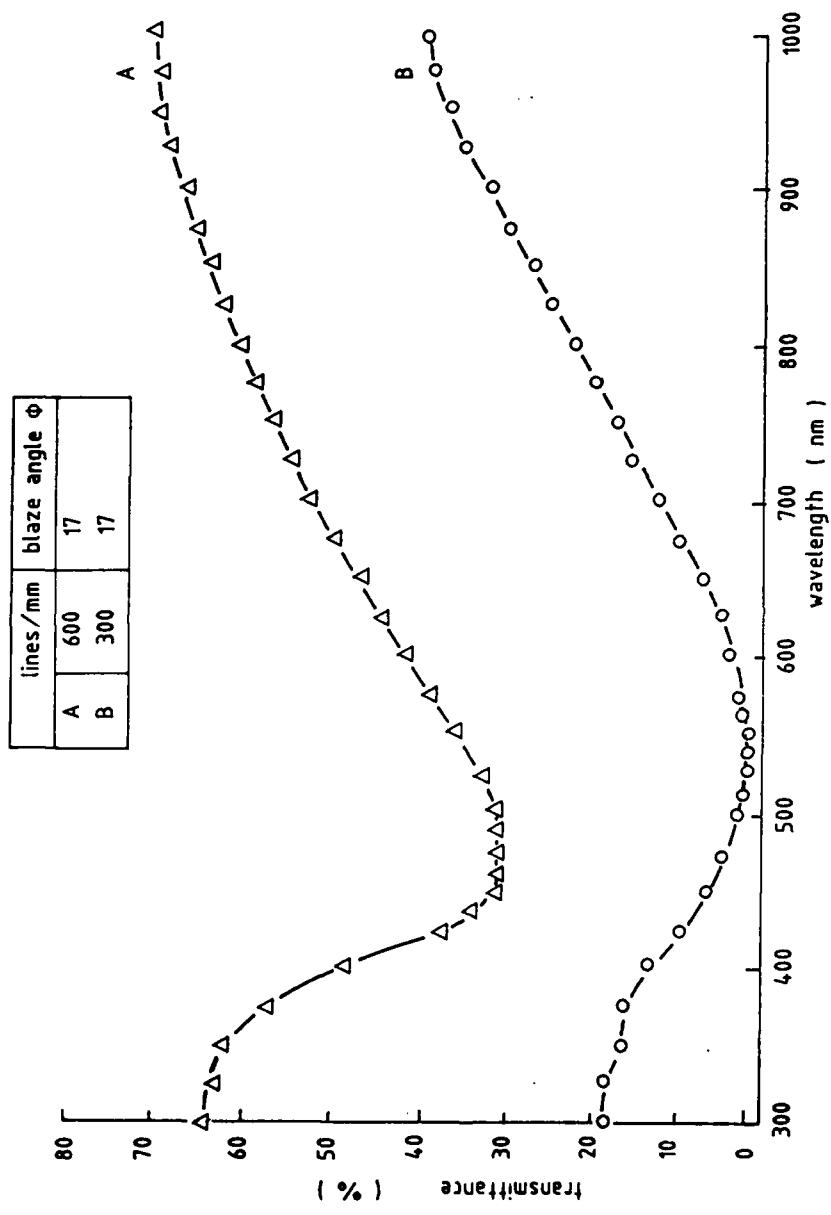


Figure 8. Effect of grating frequency on transmittance.

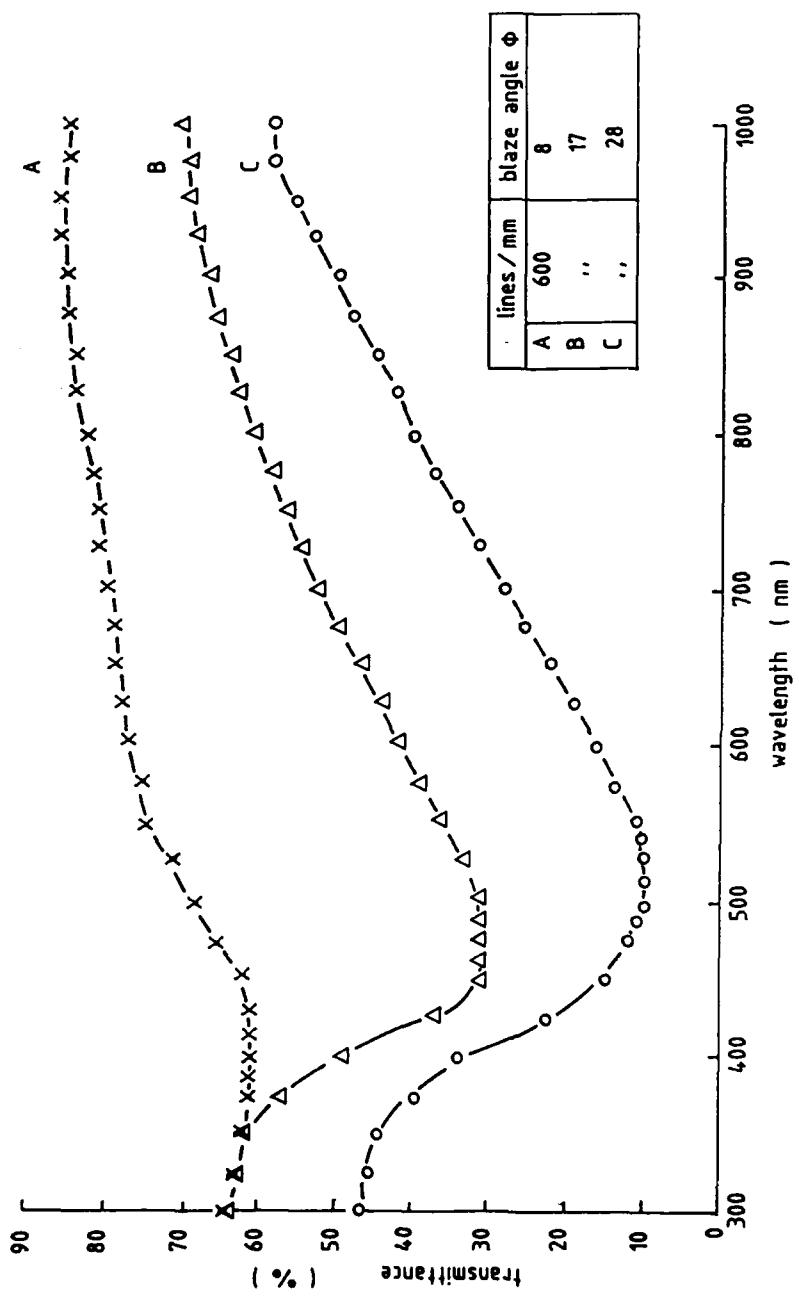


Figure 9 . Effect of facet angle on transmittance.

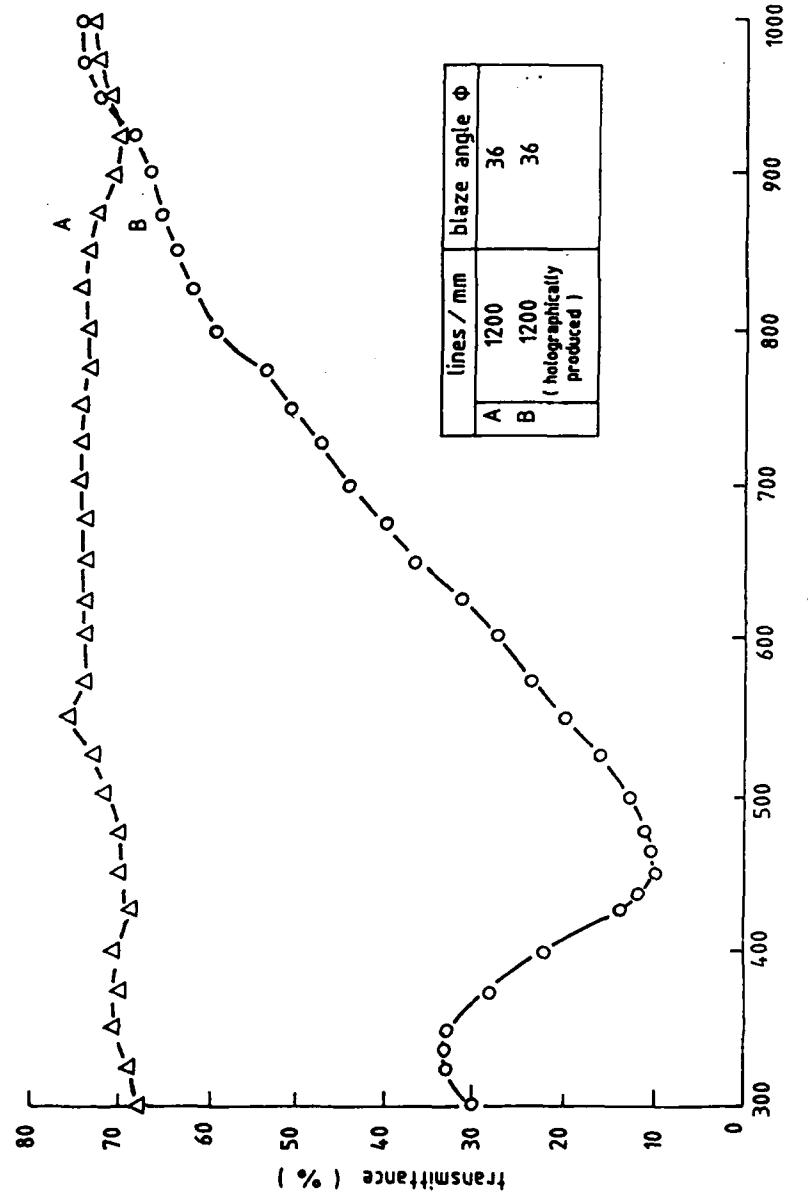


Figure 10 . Effect of manufacturing method on transmittance .

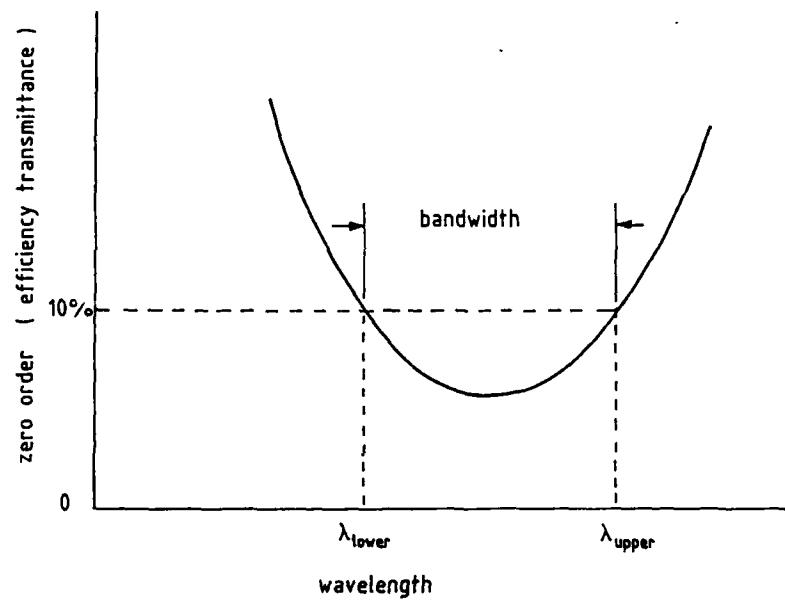


Figure 11. Bandwidth of a grating.

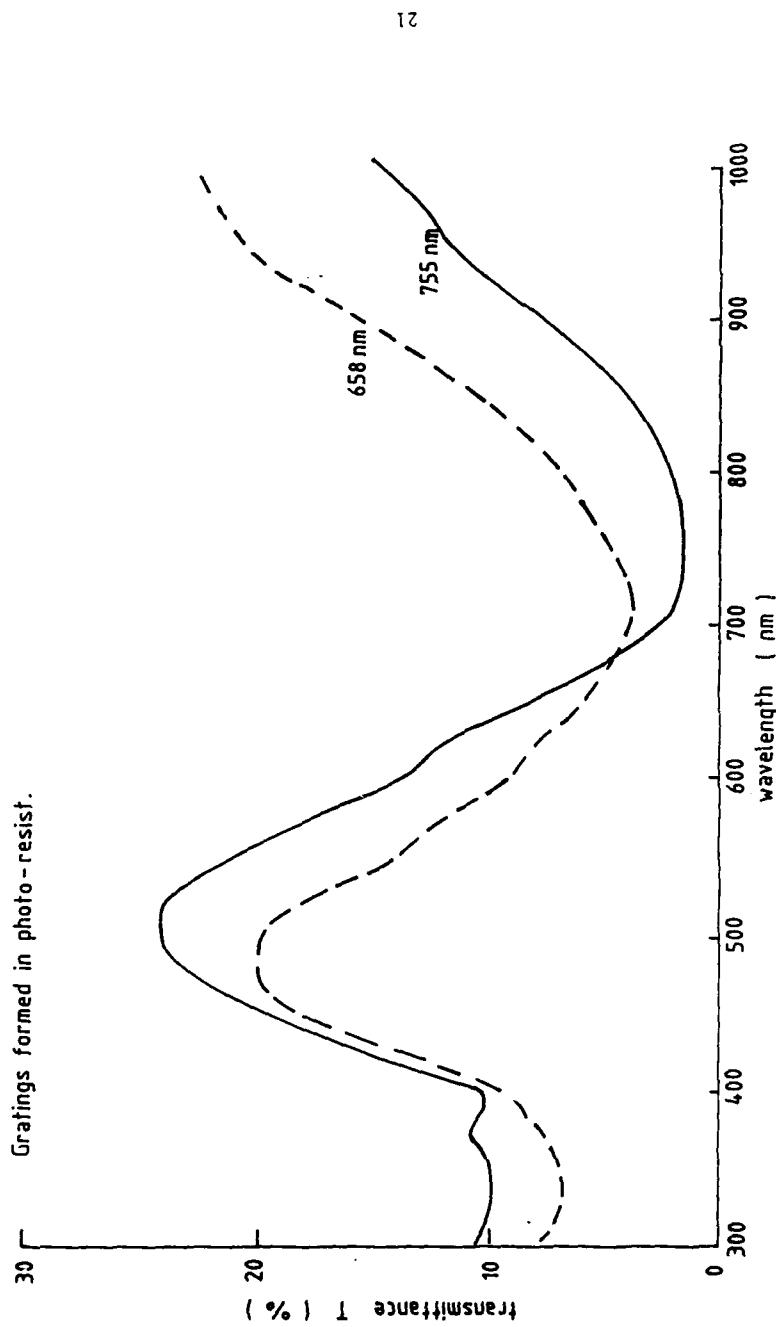


Figure 12. Effect of profile depth on transmittance with sinusoidal grating (C 3086 / 01 (groove depth 755 nm) and C 3086 / 03 (groove depth 658 nm).

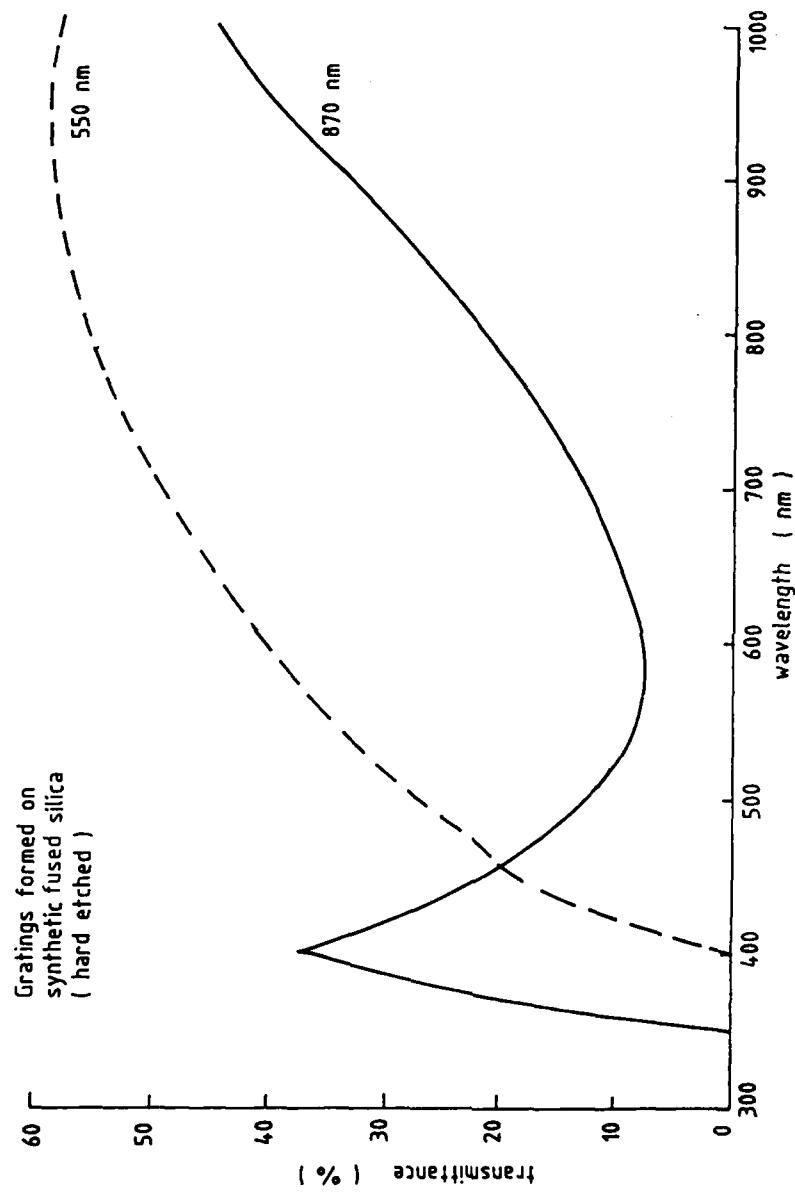


Figure 13. Effect of profile depth on transmittance with sinusoidal gratings C 3086 / 05  
( groove depth 550 nm ) and C 3086 / 10 ( groove depth 870 nm ).

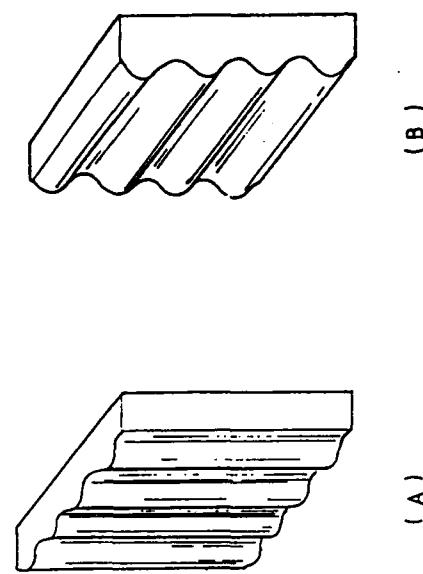


Figure 14. Multiple grating system with Sinusoidal grooves of gratings (A) and (B) being located at  $90^\circ$  orientation with respect to each other.

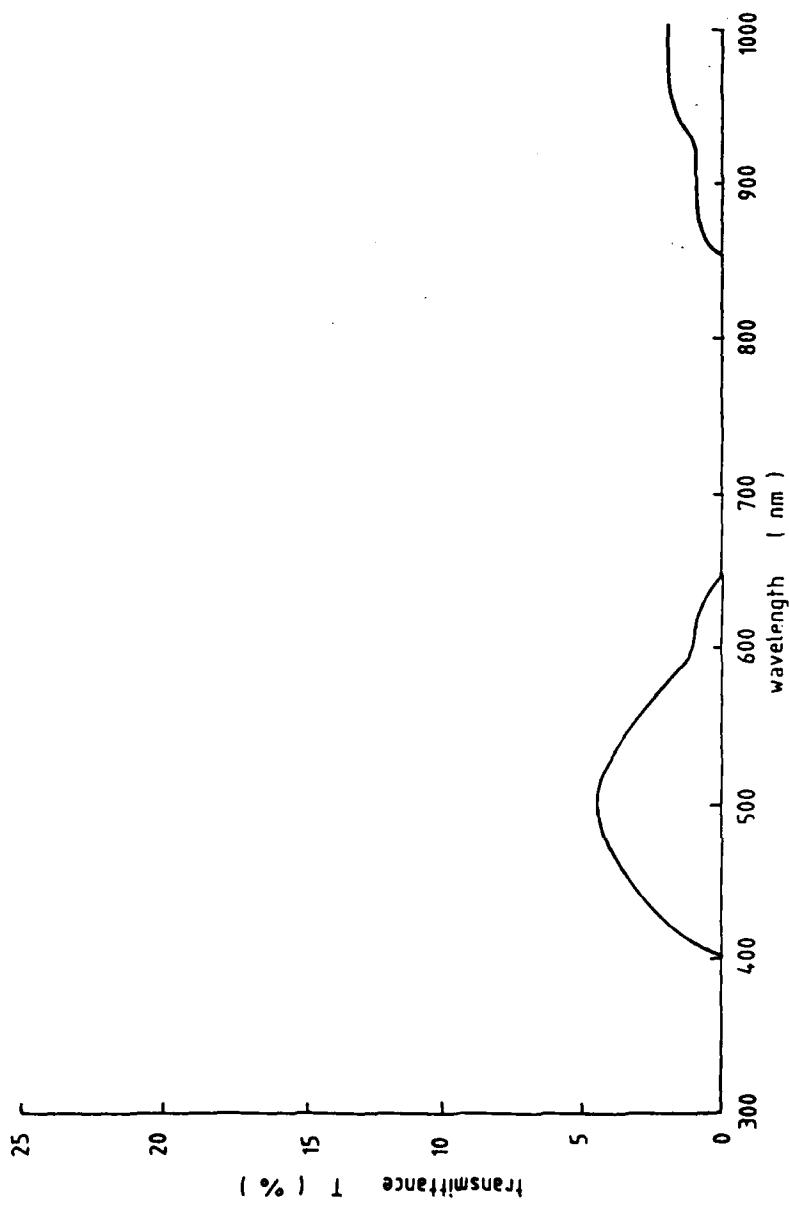


Figure 15 : Frequency response of 658 nm - 755 nm Multiple grating system in a cross-groove (90° orientation) manner for the zeroth order beam.

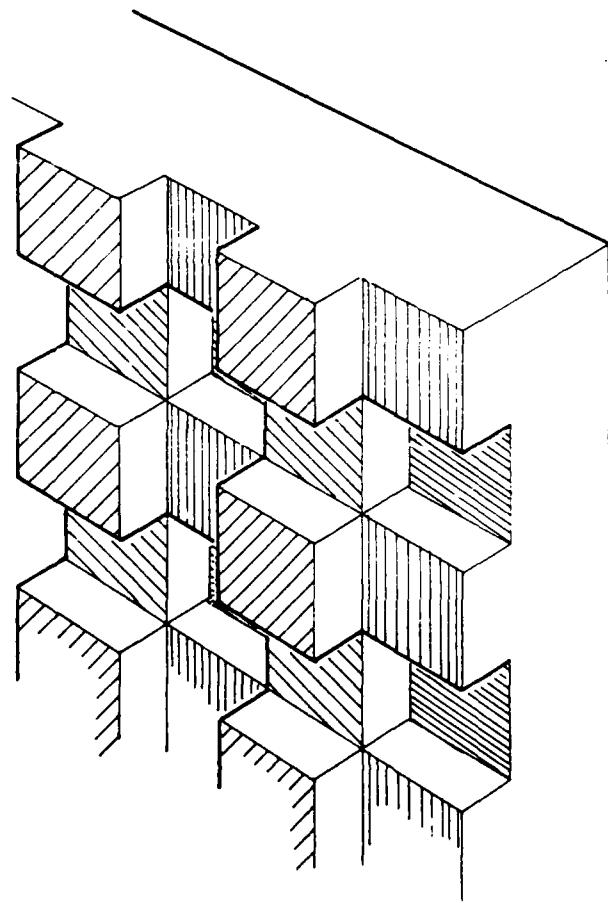


Figure 16. 2-dimensional phase grating.

## A P P E N D I X

### GRATING

NUMBER : C3086/01

Grating type : Sinusoidal transmission

Frequency :  $600\text{mm}^{-1}$

Substrate size : 30mm diameter

Grating material : photoresist (Shipley Microposit 1400-17)

Grating index : 1.64 at 633nm

Substrate material : synthetic fused silica (Spectrosil-B)

Substrate index : 1.46 at 633nm

### Zero-order

transmission : 4.5% at 633nm

### Groove amplitude $a'$

(peak-to-peak) : 755nm (estimated)

GRATING  
NUMBER :C3086/03

Grating type : Sinusoidal transmission  
Frequency :  $600\text{mm}^{-1}$   
Substrate size : 30mm diameter  
Grating material : photoresist (Shipley Microposit 1400-17)  
Grating index : 1.64 at 633nm  
Substrate material : synthetic fused silica (Spectrosil-B)  
Substrate index : 1.46 at 633nm  
  
Zero-order  
transmission : 8.0% at 633nm  
  
Groove amplitude  $a'$   
(peak-to-peak) : 650nm (estimated)

GRATING  
NUMBER : C3086/05

Grating type : etched transmission (quasi-sinusoidal)

Frequency :  $600\text{mm}^{-1}$

Substrate size : 5mm x 5mm (approx)

Grating material : synthetic fused silica (Spectrosil-B)

Grating index : 1.46 at 633nm

Substrate material : n/a

Substrate index : n/a

Zero-order  
transmission : 45.6% at 633nm  
64.1% at 870nm

Groove amplitude  $a'$   
(peak-to-peak) : 550nm (estimated)

**GRATING****NUMBER** : C3086/10

Grating type : etched transmission (quasi-sinusoidal)

Frequency :  $600\text{mm}^{-1}$ 

Substrate size : 5mm x 5mm (approx)

Grating material : synthetic fused silica (Spectrosil-B)

Grating index : 1.46 at 633nm

Substrate material : n/a

Substrate index : n/a

**Zero-order**

transmission : 15.0% at 458nm

2.0% at 633nm

20.8% at 875nm

**Groove amplitude, 'a'****(peak-to-peak)** : 870nm (measured)